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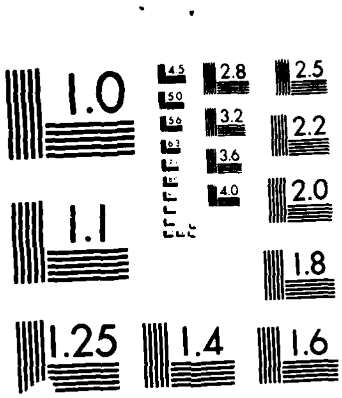


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# Microwave Hardening Technology Development Program: Final Report

by [illegible] Robert Smith,
Christopher C. Smith,
Katy D'Amico

Prepared by
Kaman Sciences Corporation
1500 Garden of the Gods Road
Colorado Springs, CO 80907

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This report summarizes the results of the tasks performed under this contract. Under HDL direction, our efforts were split between the following areas:

1. A series of microwave direct injection tests to determine burnout thresholds and upset effects for fiber-optic system components including light emitting diodes (LEDs) and PIN photodiodes.

2. An examination of the small signal and high power limiting effects of a varistor paint material applied to a co-planar waveguide transmission line when injected with microwave pulses, as well as the impact of the paint upon the normal transmission characteristics of the line such as characteristic impedance and loss.


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**22b. TELEPHONE** *(Include Area Code)*
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If more detailed information is needed on the results of these efforts, two other unpublished reports on the fiber-optics component direct injection tests and the varistor paint limiter study can be requested from HDL. Those reports provide detailed test data on each of the tasks.

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## TABLE

# 1. INTRODUCTION

This constitutes the final report for the Microwave Hardening Technology Development Program-- Phase I, performed by Kaman Sciences Corporation under a subcontract to Booz-Allen & Hamilton, Inc. (subcontract number 09004-197-K070-87). The work was funded by Harry Diamond Laboratories (HDL) under prime contract number DAAL02-86-D-0042. The purpose of this report is to provide an executive summary of the results of the tasks performed under this contract. Two other final reports[1,2] are also being submitted describing in detail the fiber-optics component direct-injection tests and the varistor paint limiter development effort.

The goals of the program were:

- to examine and rank, according to priority, the microwave hardening requirements of the Army, Navy, and Air Force,
- to examine and classify hardening approaches which could meet these needs,
- to carry out the development, fabrication, testing, and evaluation of a prototype hardening device selected by HDL (from a list of recommendations which Kaman provided approximately midway through the program), and
- to investigate fiber optics, in particular, as a microwave hardening approach (this was a particular interest expressed by the Air Force).

There were two parts to this program. In the first part, we completed the first three tasks in the statement of work by examining the basic, microwave hardening requirements of the Army, Navy, and Air Force; reviewing the current microwave hardening technology; classifying hardening approaches according to their application; and providing HDL with a recommended list of microwave hardening development efforts. In addition, we investigated the use of fiber optics as a microwave hardening approach and reviewed several cost-benefit analyses comparing optical fiber to hard-wire systems. The results of these activities were reported in our interim report[3] and will not be included here. Instead, this report will focus upon activities undertaken since the interim report.

In response to our recommendations in the interim report, HDL directed us to proceed with our effort split approximately equally between two different tasks:

1. A series of microwave direct-injection tests to determine burnout thresholds and upset effects for fiber-optic system components including light-emitting diodes (LED's) and PIN photodiodes.
2. An examination of the small-signal and high-power limiting effects of a varistor paint material applied to a coplanar waveguide transmission

line when injected with microwave pulses, as well as the impact of the paint upon the normal transmission characteristics of the line such as characteristic impedance and loss.

This report contains summaries of the results of both of these tasks. For more detail the reader is referred to the corresponding, detailed final reports.[1,2]

Section 2 of this report discusses the varistor paint limiter study, while section 3 covers the fiber-optics component direct-injection tests. The summaries and conclusions of both efforts are discussed in section 4. In section 5 we present an overview of the work to be carried out under a follow-on program consisting of further testing of fiber-optic components and the development of a superconducting limiter device.

## 2. VARISTOR PAINT LIMITER STUDY

This section discusses the design, fabrication, and testing of the varistor paint limiter device.

### 2.1 RF Limiters

RF limiters are devices which tend to "clamp " or limit the excursion of circuit currents or voltages to predetermined ranges. They are often used to protect sensitive components, e.g., front ends of receivers, from damaging, high-level signals. Typical limiting devices include varistors, diodes, thyristors, spark gaps, fuses, and circuit breakers.

### 2.2 Varistors

Varistors are bulk semiconductor devices whose resistance varies with the magnitude, but not the polarity, of the applied voltage. They are composed of a polycrystalline material containing either silicon carbide or oxides of zinc and bismuth. The metal-oxide varistors (MOV's) are preferred for clamping, because they have a more nonlinear voltage and current relationship. They are extremly fast devices and can respond in less than a nanosecond.[4] Their voltage dependent impedance can be modelled as a shunt capacitance in parallel with a shunt resistance.

### 2.3 Varistor Paint

The varistors discussed above are lumped, two-terminal devices. The varistor material itself has been used for transient suppression in ac circuits, for power conditioning, and for electrostatic discharge protection[5]. It is available in a paint form[6] which has been used for circuit protection at lower frequencies. Low-frequency tests indicate that at sufficiently high power its dielectric constant increases rapidly from 10–20 to over 1000, making it attractive in capacitive shunt applications for limiting fast, high-power pulses. In addition, after about 0.4 $\mu$s, its conductivity decreases, providing a resistive shunt. For these

reasons, Kaman proposed[3] an experiment to investigate the utility of varistor material in fabricating a microwave limiter.

## 2.4 The Varistor Paint Limiter

Figure 1 shows a cross-sectional sketch of the proposed limiter. A coplanar waveguide transmission line was fabricated by vapor depositing a metal layer onto an alumina substrate. The varistor material was then "painted" over the transmission line forming a dielectric layer. Since the dielectric constant of the varistor material will reduce the characteristic impedance of the transmission line to a value less than that with air as the dielectric, the transmission line was designed for a characteristic impedance greater than 50 Ω. Then the varistor material was applied, in hope that with the varistor paint the transmission line impedance would be close to 50 Ω. Because the effect of the paint could not be predicted exactly, several transmission lines were designed with uncoated characteristic impedances ranging from 55 to 75 Ω. A test fixture was fabricated which enabled us to test the transmission line structures without having to solder to them (the films are destroyed by soldering).

## 2.5 Results

The effect of the varistor paint on the small signal properties of the transmission line was investigated using a network analyzer to measure the device S-parameters with and without the varistor paint. The additional attenuation produced by the varistor paint varied from about 1 dB/cm at 1 GHz to 20 dB/cm at 14 GHz. Figure 2 shows a plot of the additional attenuation per centimeter length due to the varistor paint versus frequency.

The attenuation characteristics of the device at high power were investigated by injecting 3-μs pulses of microwave power at nominal incident power levels of 200 W, monitoring the incident and transmitted power with directional couplers and crystal detectors, as shown in figure 3. A comparison of the attenuation measurements at high power with the low power S-parameter measurements reveals little or no limiting behavior. In addition, a comparison of high-power data for different peak power levels indicated no greater attenuation for the higher peak power pulses, contrary to that which would be expected if the device were limiting.

A comparison of the low-level attenuation properties of the varistor material before and after being stressed by the rf field is illustrated in Figure 4. Note that after being subjected to the high rf fields, the resonances (due primarily to the test fixture) are shifted slightly to higher frequencies, but the overall attenuation is relatively uneffected. The shift of the resonances to higher frequencies was surprising, since dc data[5] indicate that the capacitance per unit length should increase after the stress, which would tend to shift the resonances to lower frequencies.

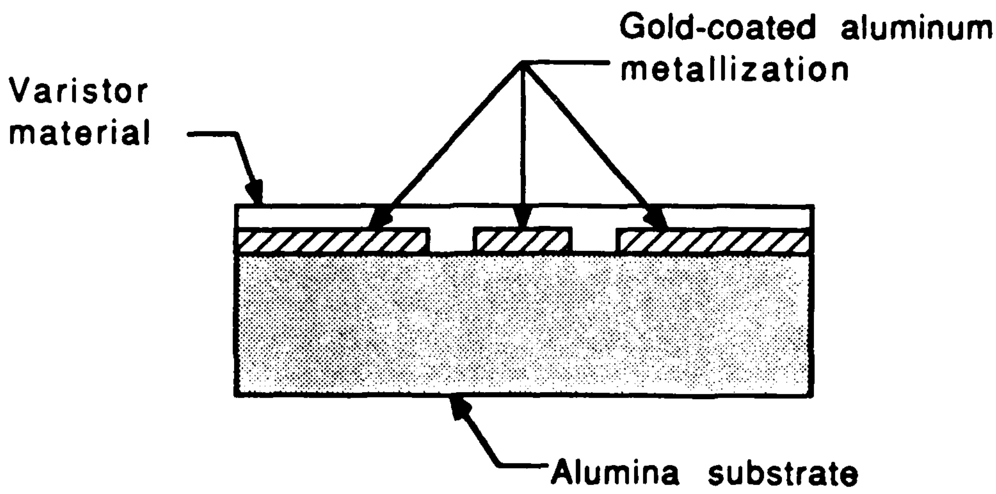



**Figure 1. Cross-sectional view of varistor limiter.**

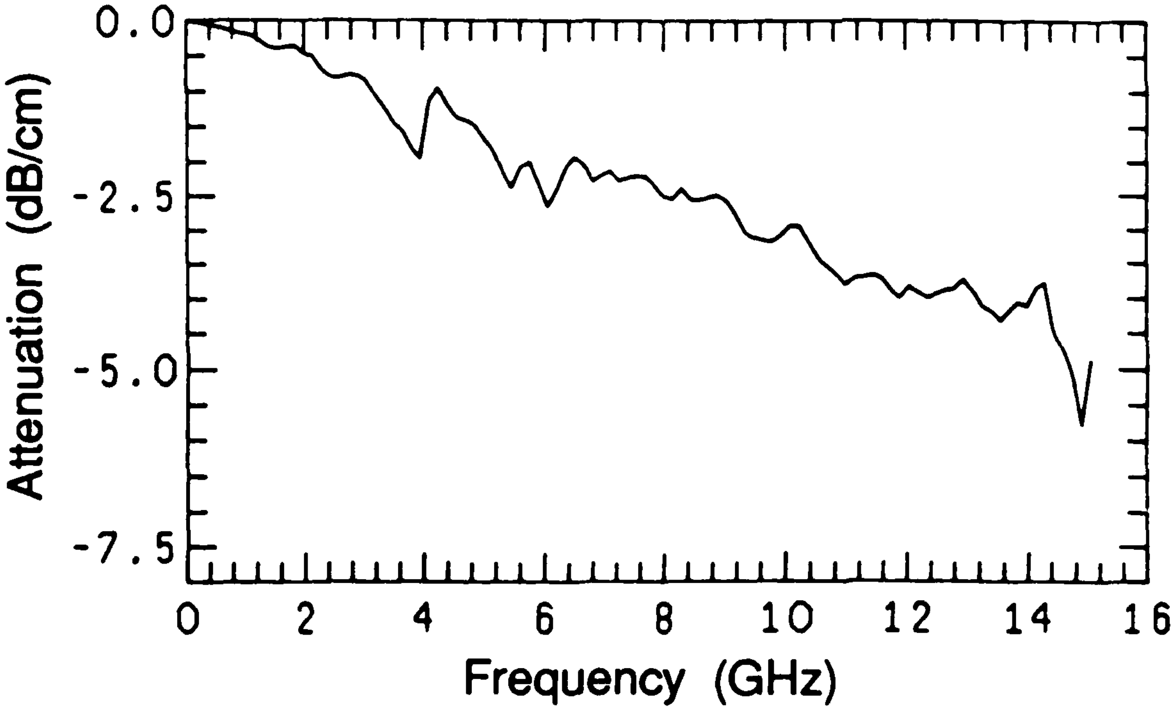



**Figure 2. Attenuation per centimeter of length by varistor paint on transmission line 70-1.**

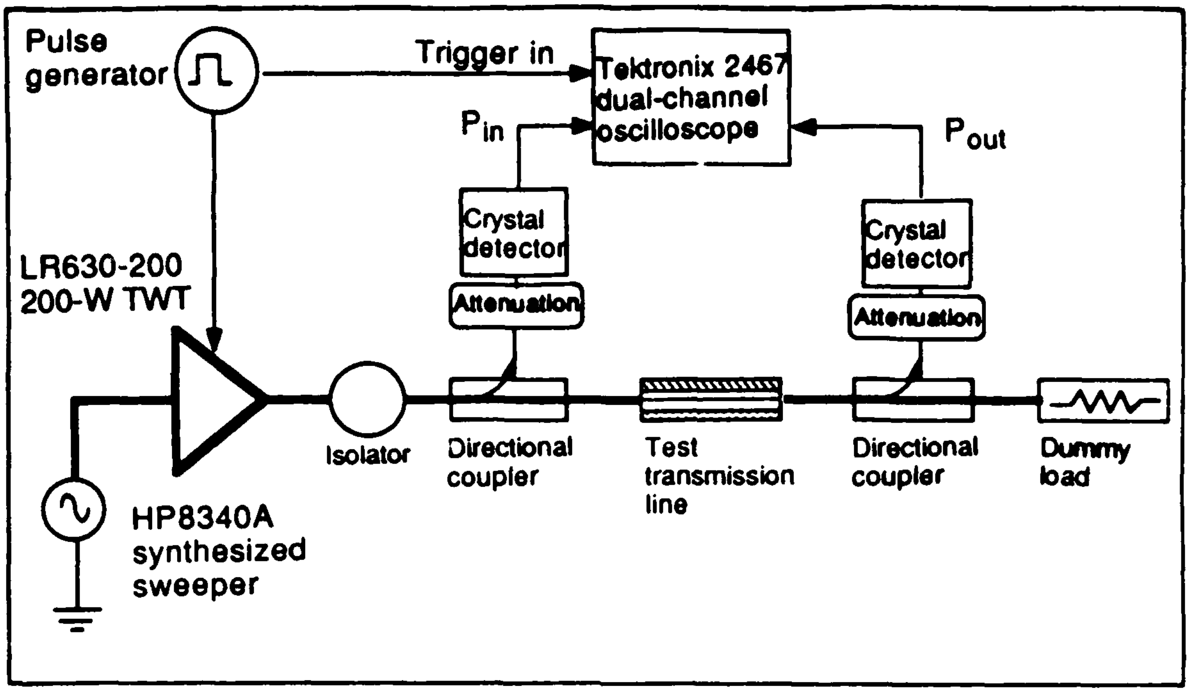



Figure 3. Microwave direct-injection test setup.

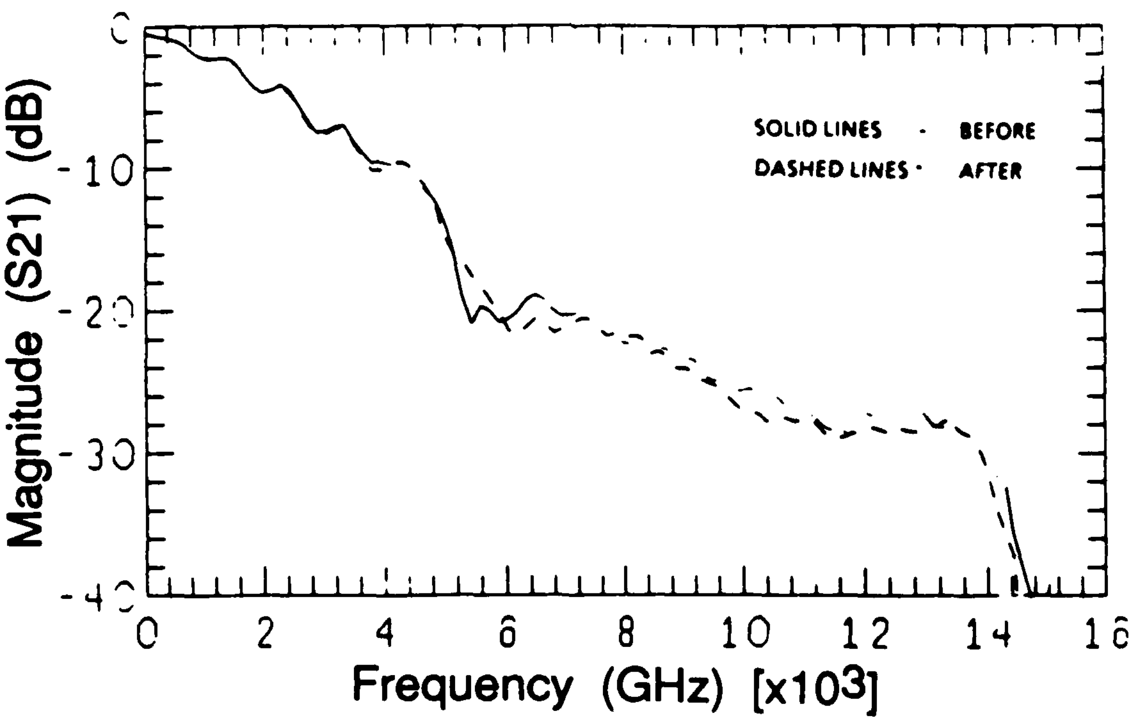



Figure 4. $S_{21}$ measurements for transmission line 75-1 before and after being subjected to 200 W rf pulses.

## 3. FIBER-OPTIC COMPONENT DIRECT-INJECTION TESTS

This section discusses the direct-injection tests carried out to determine the susceptibilities of various LED's and PIN photodiodes, commonly used in fiber-optics links, to HPM.

### 3.1 Hardening with a Fiber-Optic Link

Figure 5 illustrates the basic concept of replacing a hard-wire signal cable with a fiber-optic link to harden a system against HPM. In a typical system of interest for military applications, susceptible electronic devices are housed in shielded boxes. Shielded cables are used to carry electrical signals between the boxes. These cables and their connectors are often the principal point of entry (POE) at which HPM energy enters the system and couples to the susceptible components. In this coupling process the metallic cable braid can act as a fairly efficient receiving antenna. Currents induced on the braid produce fields which can couple to wires inside through spaces in the braid weave and at the connector backshell. Although microwave signals carried along wires inside a braided cable are usually rapidly attenuated, the length of wire to a susceptible component is often short enough that this attenuation cannot prevent burnout of the device.

The idea of a fiber-optic hardening approach is to replace the cable with an optical fiber, made of dielectric material (usually glass) and thus immune to field induced currents. The fiber penetrates the shielded boxes through wave-guides below cutoff (WGBCO) which very effectively attenuate fields below a cutoff frequency, usually at least a factor of ten greater than HPM fields of interest. However the electrical signal at the sending end must first be converted to an optical signal to carry the information over the fiber. At the receiving end, the information must be extracted from the optical beam and used to produce an electrical signal which is a replica of the original signal. For systems which are of most interest in military applications, i.e., those with comparatively low data rates transmitted over short distances, the conversion from electrical to optical is accomplished with an LED, and the inverse conversion is made with a PIN photodiode.

It is evident from figure 5 that the implementation of a fiber-optic link to replace a shielded cable results in the introduction of two new electronic components, namely, the transmitter/receiver elements at each end (assuming a bi-directional link). Knowing the susceptibilities of these components to HPM is of paramount importance if they are to be used to protect the system.

Electronic and electro-optical component susceptibilities to microwaves have been investigated both analytically and experimentally by a number of laboratories. Richardson and Puglielli[7] experimentally determined the burnout susceptibilities of various integrated circuit devices including TTL and ECL logic families and 741 op-amps. Share[8] estimated the burnout levels for certain electro-optic sensors and preamplifier devices. Saran[9] investigated the interference (break-lock) of TV, infrared, and laser-seeker systems for the Maverick missile. Face[10] has experimentally examined the frequency

dependence of pin-level burnout thresholds for various op-amps and NAND gates. Other test programs to evaluate component susceptibilities to HPM are discussed in references 11 to 14. We were not able to find any data in the literature on HPM susceptibilities of optoelectronic components used in fiber-optic systems.

If the transmit/receive components are housed safely inside a tightly shielded enclosure with no metallic interconnecting cable between boxes to couple HPM energy inside, one might reasonably question the concern for their susceptibility to HPM. Although not shown in figure 5, power for these devices and for the other electronic components inside the box must be supplied externally unless the system is battery powered. Thus, at least one wire penetration is unavoidable, i.e., the wire (or wires) providing system power, and this penetration constitutes a potential POE for the system. Then what has been gained by using a fiber-optic link? It turns out that it is often easier to provide terminal protection for a power lead than for a signal lead because of bandwidth requirements.

### 3.2 Purpose and Objectives of Component Tests

The purpose of the work described in this section was to determine the HPM susceptibilities of selected LED's and PIN photodiodes. Our objectives, therefore, were to carry out a series of direct-injection tests on a sufficient number of samples of these components to determine absorbed microwave power levels at which burnouts occur. In addition, we wanted to investigate *transient, upset effects* upon transmitted signals during the HPM injection pulse.

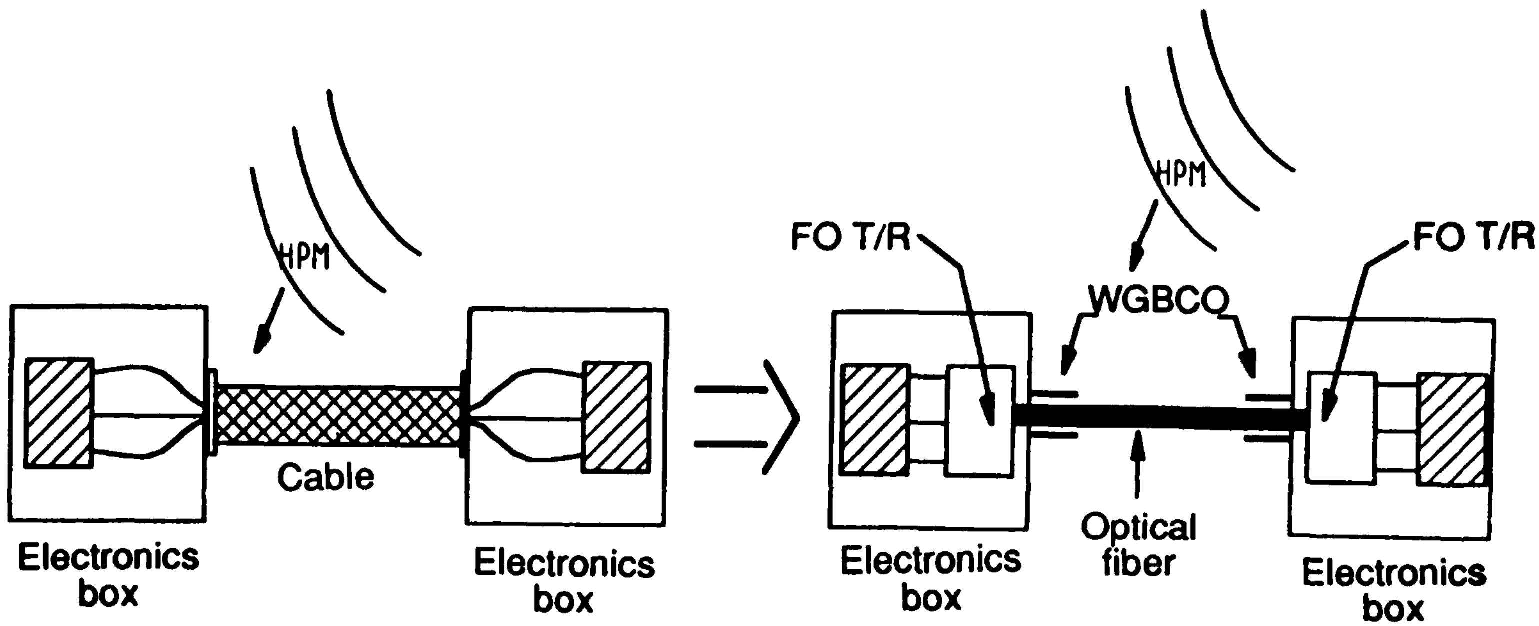
### 3.3 Components Tested

Twenty-four LED's and twelve PIN photodiodes were tested. The LED's included 14 Motorola MLED71's, 5 Motorola MFOE200's, and 5 Hewlett Packard HFBR-1402's. The silicon PIN photodiodes included 7 Motorola MRD500's and 5 Hewlett Packard HFBR-2208's. All are short wavelength (700 to 940 nm) devices and are representative of components used in medium performance links with data rates less than 100 kbit/sec over distances less than several kilometers.

### 3.4 Test Procedure

All tests were conducted with the device under test (DUT) placed in a special test fixture designed to couple microwave power into the DUT in as efficient a manner as possible and still allow for proper dc bias to be applied. VSWR measurements were made on each device prior to the injection test. For the LED's test frequencies were selected for which the DUT in the test fixture exhibited a minimum VSWR at low power-- 7.4, 6.45, and 5.0 GHz for the MLED71, MFOE200, and HFBR-1402, respectively. The PIN photodiode tests were carried out at 5 GHz. In each test the microwave pulse was applied across the diode while biased for normal operation.

The microwave pulses were produced by amplifying the output from a synthesized sweep oscillator (HP 8340B) with a 200-W TWT. A PIN diode




- Shielded cable/connectors often principal POE
- Optical fibers plus T/R replace cable

Figure 5. Hardening with fiber-optic link.

switch driven by a pulse generator (Stanford PG-535) was used to provide a rectangular microwave pulse for the tests. In a series of preliminary tests, pulse widths of 1 ms were determined to be the minimum necessary to produce burnout in the LED's. Longer pulse widths were not attempted because of limited cw power handling capabilities of some of the directional couplers used in the test setup. In a typical test sequence single pulses were applied at one minute intervals, increasing the power of each successive pulse until burnout was observed or peak output power was reached.

During the tests the forward and reflected power was monitored using directional couplers, attenuators, and crystal detectors. The outputs of the crystal detectors were observed on a dual-beam oscilloscope and recorded on film.

### 3.5 Results

Figure 6 shows typical oscilloscope traces of forward and reflected power for LED tests. In figure 6(a) no burnout was observed, and the two traces are very similar. In figure 6(b) one can see an abrupt jump in the reflected power trace which occurs at the moment of burnout. This effect was observed in all LED tests in which burnout occurred.

Figure 7(a) shows typical behavior of the LED light output during the microwave pulse when no burnout occurs. The DUT is a Hewlett Packard HFBR-1402 LED. The light output was monitored with a MRD500 photodiode, and the output voltage was displayed on an oscilloscope. Note the temporary reduction in light output during the pulse. After the pulse the light output returns to the same level as before the pulse.

Figure 7(b) shows the LED output when burnout does occur, and figure 7(c) shows the corresponding incident and reflected power pulses. Note that the light output is degraded during the first part of the microwave pulse and drops abruptly to zero at burnout. Note also that the abrupt jump in reflected power at burnout coincides with the disappearance of the light output.

Table 1 summarizes the results of the direct-injection tests. The table lists the test frequency, the number of devices tested, the number of burnouts observed, and the range of absorbed powers during the tests. No burnouts were observed with the PIN photodiodes. We believe the reason for this was that the severe impedance mismatch prevented us from getting a sufficient amount of microwave energy into the device.

## 4. SUMMARY AND CONCLUSIONS

This report discusses two activities carried out during the second part of the Microwave Hardening Technology Development Program-- Phase I by Kaman Sciences Corporation under funding from Harry Diamond Laboratories. One was an investigation of the limiting properties of a varistor paint material when used as a dielectric coating for a coplanar waveguide transmission line.

(a)

(b)

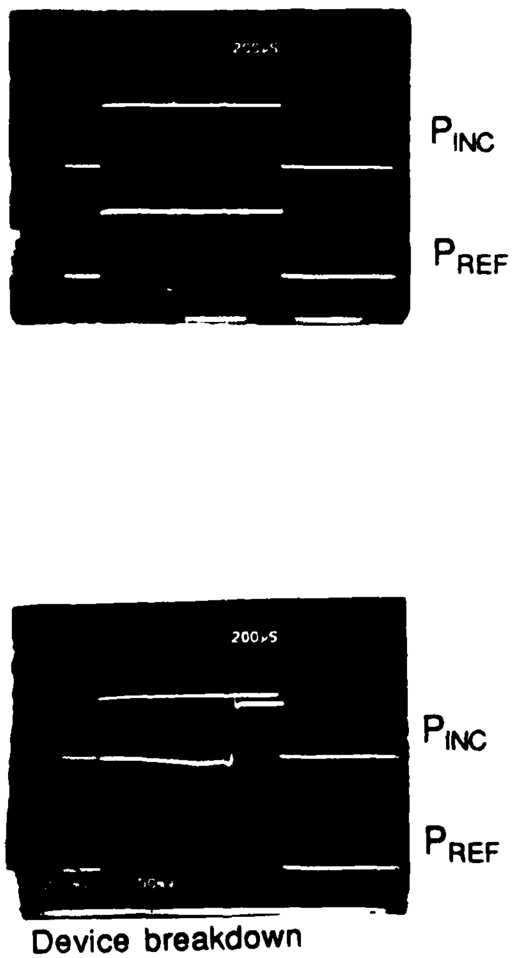



**Figure 6 Incident and reflected power measurements (a) with no burnout, and (b) with burnout.**

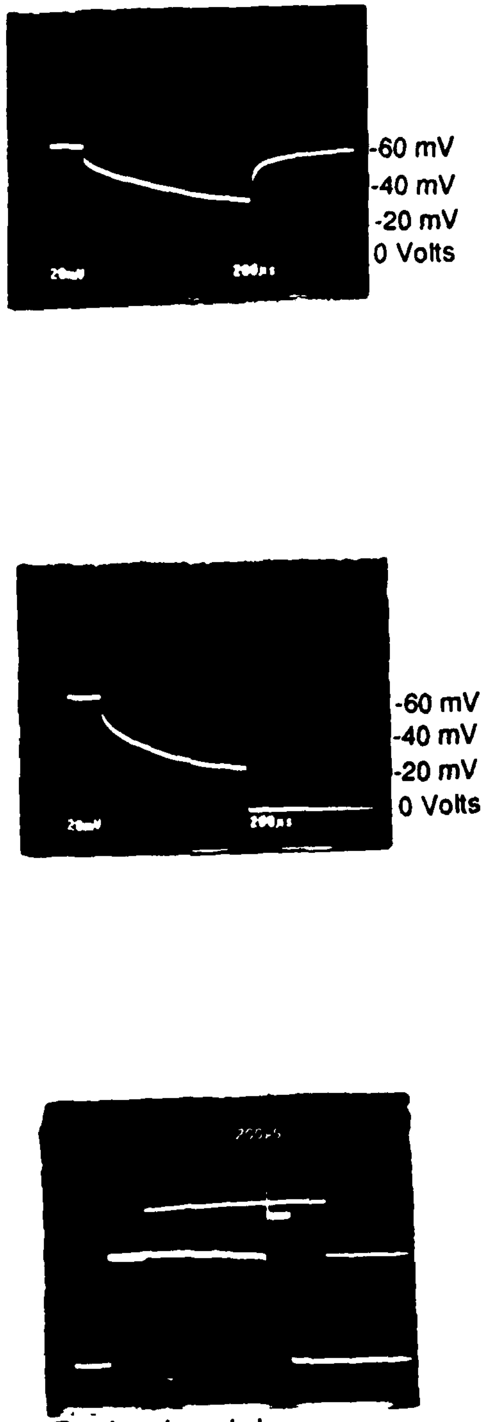



Figure 7. Degradation and recovery in light output during rf pulse HFBR-1402 #5 (a) with no burnout, (b) with burnout, and (c) corresponding incident and reflected power pulses.

Table 1. Results summary.

| Manufacturer | Model No. | Test Frequency (GHz) | No. of Devices Tested | No. of Burnouts Observed | Absorbed Power (W) |
|---|---|---|---|---|---|
| <u>LED'S</u> | | | | | |
| Motorola | MLED71 | 7.4 | 14 | 14 | 149-175 |
| Motorola | MFOE200 | 6.45 | 5 | 1 | * |
| Hewlett Packard | HFBR-1402 | 7.2 | 5 | 5 | 92-109* |
| <u>PIN DIODES</u> | | | | | |
| Hewlett Packard | HFBR-2208 | 5 | 5 | 0 | 12 |
| Motorola | MRD-500 | 5 | 7 | 0 | 75-88 |

The other was a series of microwave direct-injection tests of LED's and PIN photodiodes to determine their susceptibilities to HPM. Both activities were exploratory in nature and were intended to provide preliminary results and to point the way for further studies.

## 4.1 Conclusions of the Varistor Paint Experiment

Two principal conclusions were drawn from the results of the varistor paint study:

1. No limiting action was observed at incident powers up to 180 W for a 3-μs pulse. This was a disappointing but not surprising result for a first attempt at fabricating a microwave limiter from the varistor paint material.

2. At low signal levels no excessive distortion or attenuation was observed in the frequency range 45 MHz to 3 GHz.

We were able to test only one formulation of the varistor material. Although this particular formulation of varistor paint tested did not exhibit limiting action at the power levels available in this experiment, it is entirely possible that a different paint formulation would exhibit limiting below 200 W. It was recognized at the start of the program that several iterations might be necessary before a useable formulation could be produced. Any future program should provide funds and sufficient time to investigate several different material formulations in an iterative manner, as the results obtained with one formulation points the way for changes to be made in the next.

The power we could deliver to the device was limited by the capability of our TWT amplifiers (200 W nominal output power). It is entirely possible, even with the present formulation, that limiting could occur at higher power. Also, the test fixture design did not provide a good impedance match. We would therefore recommend that further investigations begin with a redesign of the test fixture to provide a better 50-Ω impedance match and less attenuation of the microwave signal.

A possible mechanism for the shift in resonances to higher frequencies has been suggested.[15] Initially many particles in the paint may be in ohmic contact with neighbors. Small currents may heat the contact points and form new dielectric layers between the particles, decreasing the bulk capacitance. At higher power breakdown of the dielectric films occurs, welding the particles together and raising the bulk capacitance.

Finally, we recommend that future tests investigate the utility of an adjustable dc bias across the transmission line just below the dc limiting point. Figure 8 shows a test setup which includes a dc bias. In this way the threshold could probably not only be reduced, but also be a quantity which could be adjusted to suit the needs of the particular application.

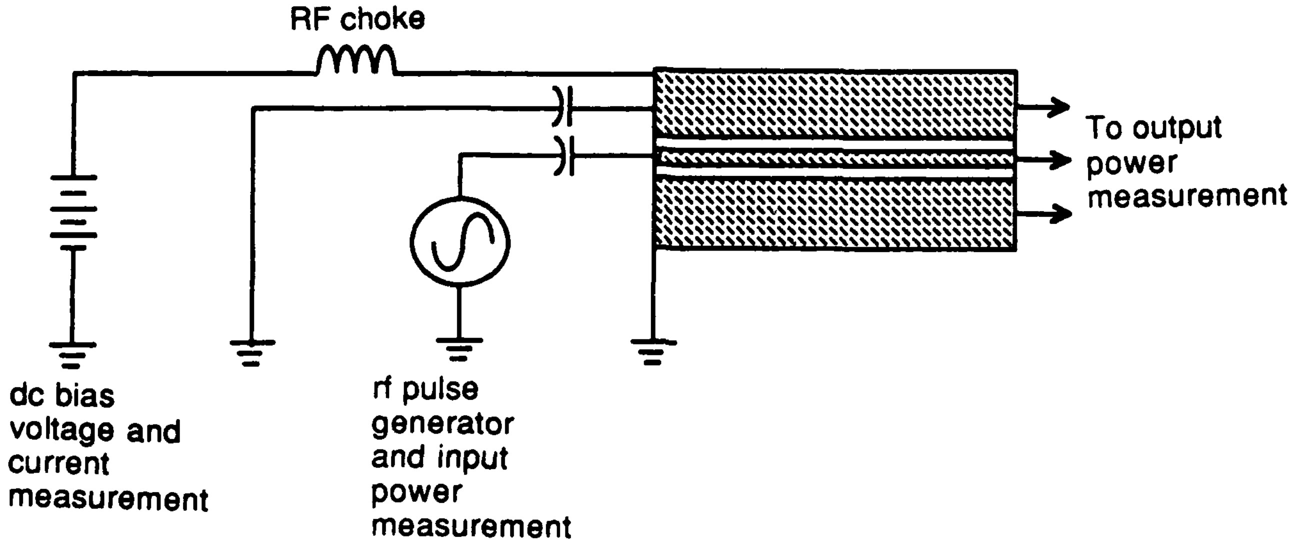



Figure 8. Varistor paint limiter with dc bias.

## 4.2 Conclusions from the Fiber-Optic Component Direct-Injection Tests

Principal conclusions derived from the results of these tests are as follows:

1. Burnout was observed in most of the LED's at absorbed power (energy) levels from 92 to 175 W (mJ) and was accompanied by an abrupt increase in reflected power.

2. A degradation in light output from the LED's was observed during the injected microwave pulse even at low values of absorbed power, but, in the absence of burnout, the light output returned to its normal level immediately after the pulse.

3. No burnouts were observed in the PIN photodiodes tested, presumably because the impedance mismatch prohibited us from delivering more than about 90 W into the device.

For future work we would recommend the following:

1. A sufficient number of burnouts (at least 50) of an LED of the same type to obtain a statistical distribution of burnout levels. This could be accomplished with the remaining MLED71's which were purchased under the present contract.

2. Postmortem analyses of failed LED's to determine where the devices failed; e.g., at the junction or metallization. One may be able to observe the junction area with a microscope looking through the plastic lens on the device itself.

3. Investigation of LED's and PIN photodiodes designed for use in the long wavelength region (1150 to 1550 nm). Although more expensive, long wavelength components are of particular interest for military systems, since 1300-nm fibers tend to be more radiation hard than those optimized for shorter wavelengths.

4. Investigation of the effects of the observed LED "upsets," i.e., the decrease in optical power during the injected microwave pulse, upon a fiber-optic data link. The microwave pulses would be injected directly into an LED while it is transmitting data over a fiber optic link. The effect of the upset upon the received data would be studied.

# 5. OVERVIEW OF HARDENING DEVELOPMENT PROGRAM-- PHASE II

In this section we discuss the elements of a proposed follow-on program consisting of three basic efforts:

- additional testing of fiber-optic components, including upset testing of a fiber-optic digital data link and burnout testing of long wavelength fiber-optic components.

- a survey of the current and projected uses of fiber optics within military systems.

- exploratory investigation of a novel limiter concept utilizing a field-induced superconducting-to-normal transition to limit the microwave power delivered to a load.

These three activities are discussed in turn in the following paragraphs.

## 5.1 Additional Fiber-Optic Component Testing

In our phase I effort we identified susceptibilities of LED's to burnout by HPM. In this follow-on effort we plan to obtain sufficient burnout data on a single LED type to determine the statistical distribution of burnout levels. In addition, we will be investigating the burnout of longer wavelength LED's and PIN photodiodes (1150 to 1550 nm) representative of those expected to be employed in future military fiber-optic systems. We will also study the effects of injected microwave pulses upon a complete fiber-optic data link while transmitting and receiving data as a result of the observed degradation of light output in the LED during microwave pulses.

## 5.2. Military Fiber-Optic Use Survey

Science and Engineering Associates (SEA) in San Diego, California, will conduct this part of the phase II effort under subcontract to Kaman. The primary task will be to survey current and projected uses of fiber optics throughout the Department of Defense and in the commercial sector, with emphasis upon defense applications. This effort will include some of the more recent fiber-optic systems such as the Navy AEGIS program, the Air Force ATF PAVE PILLAR, and the Army TRACKWOLF programs. The study will address military and commercial uses planned for the near term (5 to 10 years). Included also will be a survey of recent research and development activities including integrated optics, fiber-optic sensors, and glass development efforts. The survey information will form the baseline from which elements which drive the selection of fiber optics for systems, as well as the stumbling blocks inhibiting the use of fiber optics, can be identified.

## 5.3 Superconducting Limiter

The proposed superconducting limiter is a transmission line, either coaxial or coplanar, whose conducting elements are made of films of one of the new, high-temperature superconducting materials such as $YBa_2Cu_3O_x$. The limiter is refrigerated so that, for normal, low-level microwave signals, the conducting elements are superconducting, and conduction losses are very low. (ac signals, unlike dc, experience some loss in superconductors, although at the frequencies of interest, they are usually lower than for copper.) When

sufficiently high-power microwave signals are experienced, however, the currents are sufficient to drive the conducting elements into the normal state. The critical current level depends upon the material, the film thickness, the temperature, and any bias magnetic field which may be present. Once the transition has occurred the absorptive and reflective properties of the line are expected to change and effectively limit the microwave power which the device can pass. The thrust of the work during this program phase will be to design a suitable transmission line structure and conduct a proof of principle experiment to determine how much limiting the device can provide and how fast the limiting state can be activated. The superconducting films will be fabricated for Kaman by the Department of Electrical Engineering at the University of Colorado at Colorado Springs (UCCS) in their Microelectronics Research Laboratory. UCCS has been fabricating excellent-quality superconducting films of Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O for Kaman for almost a year under a Kaman internal reasearch and development program.

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